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REPLY TO THE COMMENT BY D. D. BLACKWELL AND G. R. PRIEST ON "*HEAT FLOW FROM FOUR NEW RESEARCH DRILL HOLES IN THE WESTERN CASCADES, OREGON, U.S.A.*" BY S. E. INGEBRITSEN, M. A. SCHOLL AND D. R. SHERROD [*Geothermics* 22, 151–163 (1993)]

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We appreciate the opportunity to elucidate our thinking with respect to the issues raised by Blackwell and Priest (1996; hereinafter B&P). Their commentary criticizes our analysis of heat-flow data from the north-central Oregon Cascades. In their view, we have relied too heavily on low-quality data, misinterpreted the data from some key drill holes, and contoured the data set in a misleading or overly detailed fashion. Here we will show that the differences between our heat-flow map and that of B&P do not depend on the details of the data set, but do depend fundamentally on how the data are interpreted and contoured.

This reply is not a detailed, hole-by-hole rebuttal of the B&P commentary; such an approach would only obscure the fundamental differences between our respective analyses. Instead, we will highlight these differences by focusing on the "correct" data set endorsed by B&P (their Fig. 1).

We do feel compelled to make at least a nominal defense of our own individual heat-flow interpretations, which we feel are generally as reasonable as those of B&P. However, instead of belaboring our own reasoning here, we simply encourage interested readers to refer to earlier publications. Our previous tabulations of the heat-flow data include the heat-flow estimates published by Blackwell and colleagues, along with their supporting data, so that the source(s) of any disagreement will be clear (Ingebritsen *et al.*, 1988, pp. 7–33; 1994, pp. 73–86). As mentioned in the B&P commentary, our tabulations omitted certain heat-flow estimates reported by Blackwell *et al.* (1990). This was a conscious omission. Our tabulations were restricted to public-domain data, and the temperature–depth data upon which the omitted estimates were based had not been released. However, in the analysis below we include all of the heat-flow estimates endorsed by B&P.

HOW TO CONTOUR THE HEAT-FLOW DATA?

Here we will show that the differences between our heat-flow map of the north-central Oregon Cascades and that of B&P depend fundamentally on how the data are contoured, rather than on the details of the data set. This will be accomplished by treating our own version of the heat-flow data set and B&P's "correct" version in exactly the same way.

Our own earlier heat-flow maps (e.g. Fig. 1) were based on the larger heat-flow data set tabulated by Ingebritsen *et al.* (1994, pp. 73–86). Values of heat flow were estimated at the nodal points of a 5-km by 5-km grid, by calculating an inverse-distance-squared weighted average of the nearest data points in each of four quadrants. Heat flow was contoured from the gridded surface. The gridding and contouring were done with SURFER™, a commercial contouring program. Certain data were excluded in the gridding; for example, those from drill holes identified as nearly isothermal or advectively disturbed (see Ingebritsen *et al.*, 1994, p. 36). The contours were not extended into the younger volcanic rocks (younger than about 7 Ma) because, as B&P note, drill holes in those rocks generally show low-to-zero heat flow to the depths of conventional measurements (100–200 m) as the result of copious groundwater recharge.

The version of the heat-flow data set regarded as correct by B&P (their Fig. 1) excludes or reinterprets many of the data used to generate our contour map (Fig. 1 herein). Nevertheless, applying the same contouring algorithm to B&P's version of the data set results in a set of contours (Fig. 2) similar to our own (Fig. 1) and very different from B&P's (their Fig. 1). Both maps generated by the inverse-distance-squared algorithm show lobate heat-flow highs associated with hot-spring groups and significantly lower values between hot springs, whereas the B&P map is dominated by a N–S-striking heat-flow gradient west of the Quaternary volcanic rocks in the Cascade Range (the Quaternary volcanic arc).

The question then arises as to whether any objective algorithms can give rise to contours more similar to B&P's. It seems reasonable to assume that the Cascade Range possesses N–S anisotropy, and by using a kriging algorithm and invoking a severe (10:1) N–S anisotropy we were able to generate a set of contours (Fig. 3) that shows a similar steep, linear N–S-striking heat-flow gradient west of the Quaternary arc. We regard this set of contours as being in qualitative agreement with those of B&P. The kriged heat-flow pattern east of the heat-flow gradient is significantly more complex than in B&P's map (compare Fig. 3 with their Fig. 1), with the large, uniform area of 100 mW m^{-2} heat flow broken into warmer and cooler subareas. However, the data coverage over much of this area is poor. B&P's tacit assumption that heat flow beneath the Quaternary arc is generally $\geq$100 mW m^{-2} seems reasonable to us, and would supersede much of the objective contouring.

Both the B&P contours and the contours generated by the kriging algorithm are highly smoothed and heavily weighted in the N–S dimension, such that the contours no longer honor many of the individual heat-flow data (see e.g. their Fig. 1). Given this approach to

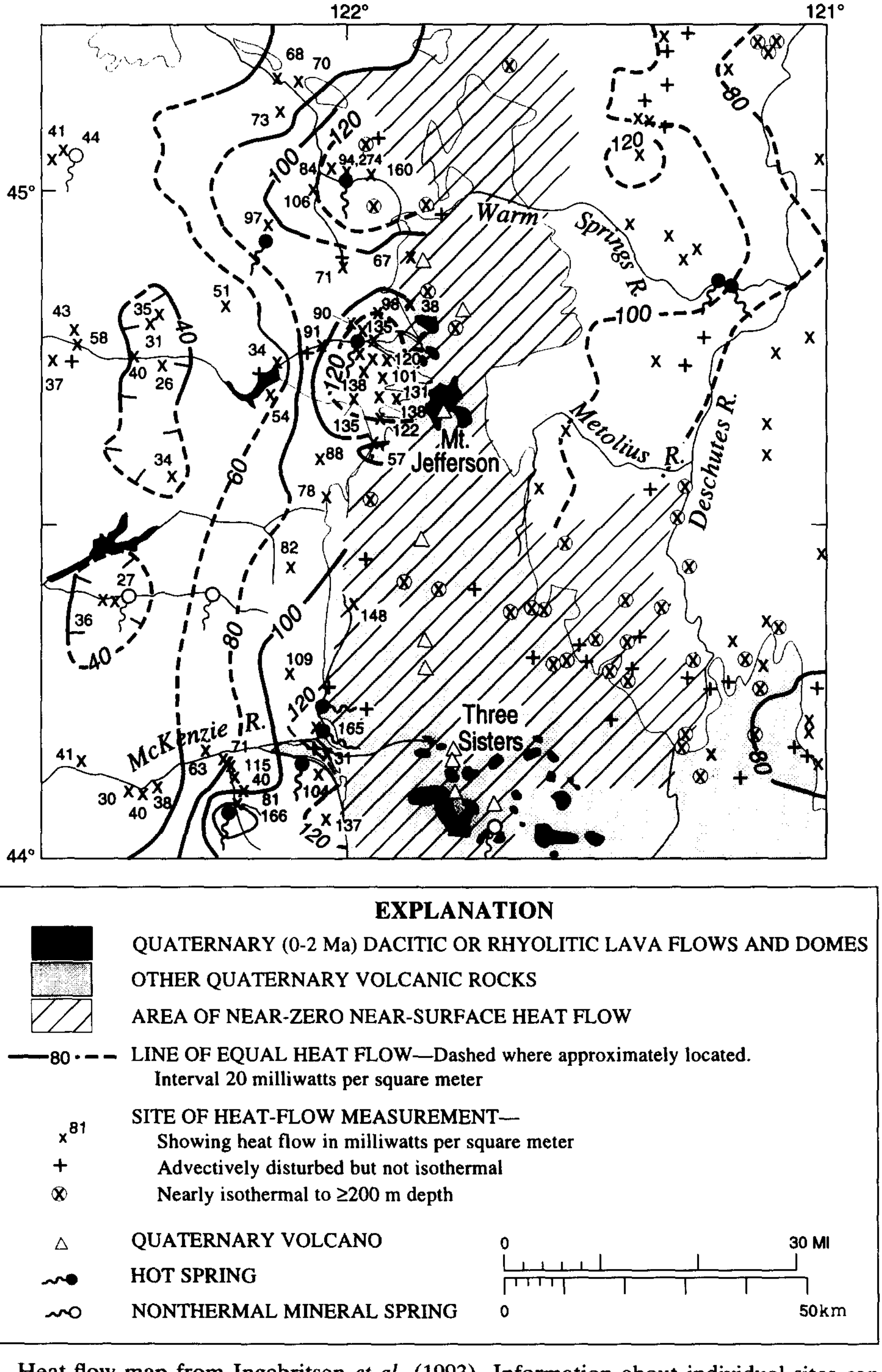

Fig. 1. Heat-flow map from Ingebritsen *et al.* (1993). Information about individual sites can be found in Ingebritsen *et al.* (1994, pp. 73–86).

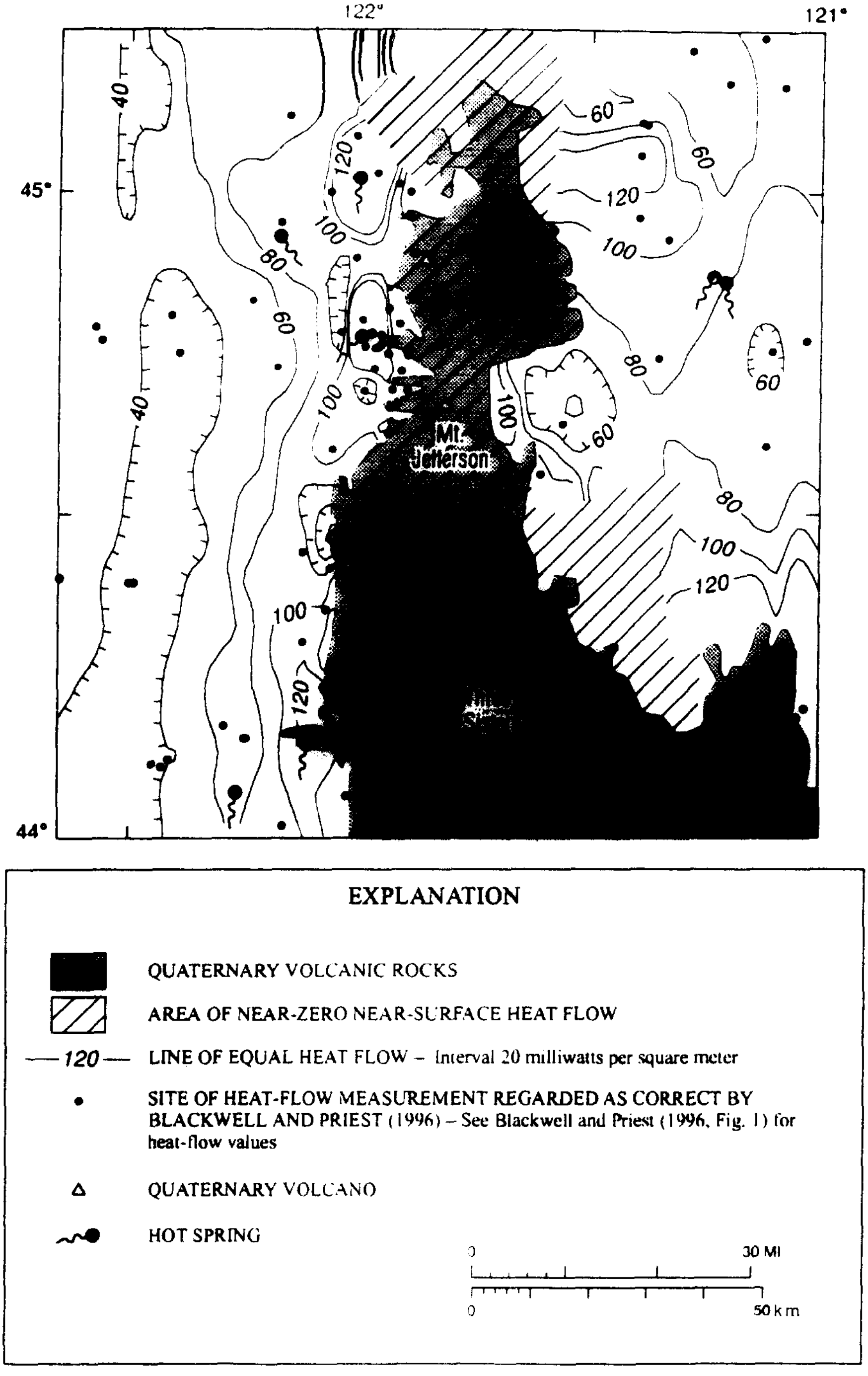

Fig. 2. Heat-flow map generated from the data set regarded as correct by B&P (their Fig. 1), using the same contouring algorithm that was used to generate Fig. 1.

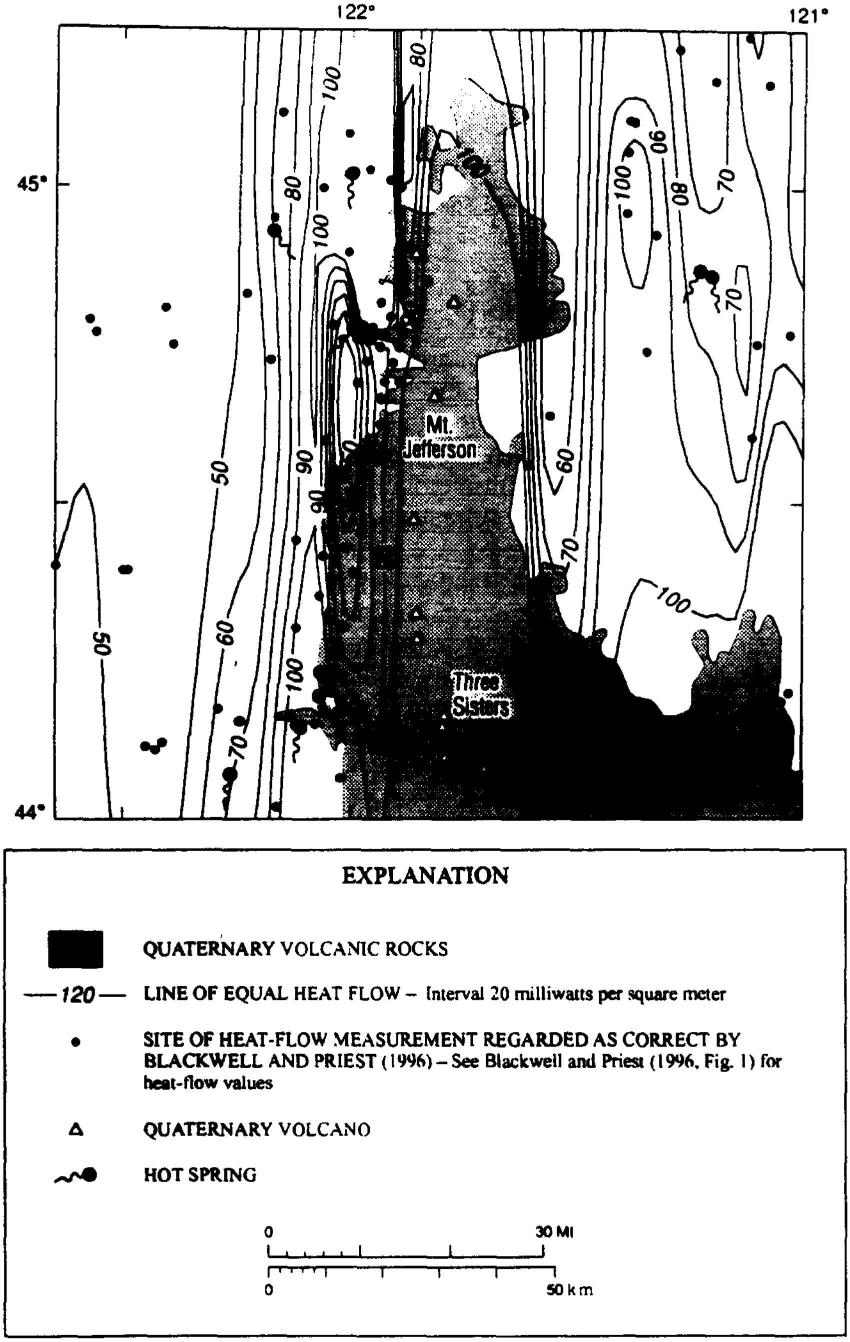

Fig. 3. Heat-flow map generated from the data set regarded as correct by B&P (their Fig. 1). Here we attempt to replicate B&P's contours by using a kriging algorithm and weighting the data much more heavily in the N–S dimension than in the E–W dimension (a 10:1 anisotropy, such that a datum that is 10 km N or S of a grid point is weighted as heavily as a datum that is 1 km E or W of the grid point).

contouring, it is nearly impossible to test the validity of the contours by simply drilling a few new holes in strategic locations. From this perspective, our limited test-drilling program (Ingebritsen *et al.*, 1993) was bound to fail. Regardless of the heat-flow values obtained, the contours were unlikely to change significantly. In contrast, the inverse-distance-squared contouring algorithm we used, which is more akin to how one might contour the data by hand, honors nearly all of the data points. Given this approach, a few new heat-flow values in undersampled locations might result in substantially different contours.

HYDROGEOLOGIC CONSIDERATIONS

Some of the differences between our approach and that of B&P likely stem from our differing backgrounds and perspectives. B&P approached the data from a crustal heat-flow perspective. In the tradition of that discipline, they strove to detect a midcrustal signal *through* near-surface perturbations such as groundwater flow. In contrast, we approached the data from a hydrogeologic perspective; our main interest is in those perturbations and what they reveal about patterns of fluid circulation.

We still frankly doubt that it is possible to see through the effects of groundwater flow on these particular data. In the Cascade Range, copious precipitation (locally >2.5 m per year), extensive exposures of permeable volcanic rock, and large topographic gradients (~1:10) combine to ensure vigorous groundwater flow, at least at shallow depths. Groundwater recharge rates exceed 1 m per year over large areas of the Cascades (Ingebritsen *et al.*, 1992; 1994, pp. 16–18), whereas vertical flow rates of only a few cm per year are sufficient to grossly distort the Earth's thermal field (e.g. Bredehoeft and Papadopolous, 1965).

The B&P commentary suggests that heat-flow measurements in deeper holes prove the reliability of heat-flow values determined in shallow holes. We hold a nearly opposite view and cite the temperature–depth data shown in Fig. 4 as the basis for our skepticism. All of the deep (>460-m depth) holes in the study area show major, hydrologically forced changes in temperature gradient (Fig. 4A), such that the temperature gradients measured in the depth range of a typical heat-flow hole (<200 m) are substantially different from those observed at greater depths. Despite B&P's argument that older (>5 Ma) volcanic rocks have negligible permeability, temperature reversals are seen to occur due to thermal-fluid circulation in such rocks. For example, in the Breitenbush Hot Springs area, the conductive gradients seen in numerous 150–500-m-deep drill holes are likely controlled by a thermal aquifer in >20-Ma rocks at ~800 m depth (Fig. 4B; see Priest *et al.*, 1987, for a description of the thermal aquifer). Because of the paucity of deep drill holes in the older rocks, it is impossible to say whether such disturbances are widespread. However, on the basis of the existing set of observations in the vicinity of the heat-flow transition (Fig. 4), we maintain that it is imprudent to project shallow temperature profiles from this region to midcrustal depths.

The abrupt heat-flow gradient mapped by B&P west of the Quaternary arc (see their Fig. 1) depends largely on a set of more local heat-flow anomalies associated with hot-spring areas. The hot springs occur across a narrow elevation range (440–680 m above sea level), in deeply incised valleys that capture regional groundwater flow from the Quaternary arc. They occur at roughly the same longitude, so that when the local heat-flow data are sufficiently smoothed and elongated in a N–S direction, a continuous heat-flow gradient

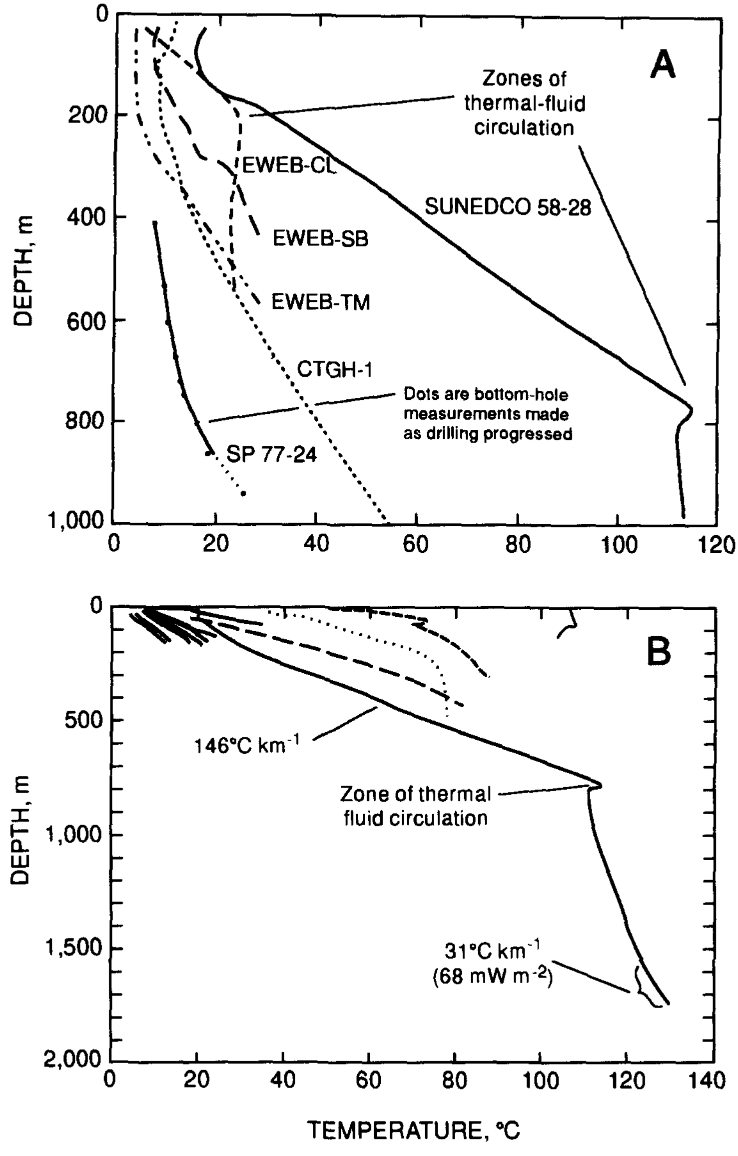

Fig. 4. (A) Temperature–depth data from relatively deep (>460 m) drill holes in the study area. Heat-flow values from EWEB-SB, EWEB-TM, and EWEB-CL were reported by Blackwell *et al.* (1982), CTGH-1 and SUNEDCO 58-28 by Blackwell and Baker (1988), and SP 77-24 by Blackwell (1992). (B) Temperature–depth profiles from drill holes in rocks older than 7 Ma in the Breitenbush Hot Springs area (Blackwell and Baker, 1988; Ingebritsen *et al.*, 1988; Blackwell *et al.*, 1990). Seventeen shallow holes (<500 m deep) have high gradients that generally correspond to heat flows >110 mW m^{-2}. However, a similar gradient in the upper part of the deepest hole (SUNEDCO 58-28) changes abruptly below a zone of thermal-fluid circulation in >20 Ma rocks at ~800 m depth, suggesting that the gradients in the shallow holes are also controlled by groundwater flow.

appears (e.g. Fig. 3, or B&P's Fig. 1). When the data are not smoothed, a more lobate set of heat-flow anomalies emerges (Figs 1 and 2).

Blackwell *et al.* (1982) considered and rejected a "lateral-flow" model that explained the heat-flow gradient west of the Quaternary arc in terms of groundwater flow towards the hot springs. We chose to resurrect this model for three reasons. Firstly, stable-isotope data indicate that the hot springs are likely recharged in the Quaternary arc, at elevations of about 1300–1900 m above sea level (e.g. Ingebritsen *et al.*, 1989, Fig. 2). Secondly, a heat-budget analysis showed that the heat transferred from the Quaternary arc *via* groundwater flow is sufficient to account for the anomalously high heat flow observed west of the arc (Ingebritsen *et al.*, 1989; 1994, pp. 41–44). Finally, we were attracted to a model that did not require a widespread midcrustal heat source extending west of the area of active volcanism.

Blackwell and colleagues prefer to explain the heat-flow gradient west of the Quaternary arc in terms of a midcrustal heat source related to magmatic intrusion. Their major argument in support of a wide midcrustal heat source has been an apparent correlation between their heat-flow and gravity gradients (e.g. Blackwell *et al.*, 1982, 1990). However, recent analysis has indicated that both the gravity and heat-flow gradients must be shallow rooted (<2.5 km and <5 km, respectively; Blakely, 1994). The shallowness of the causal heat and mass distributions could both be related to lateral flow of heated groundwater confined to a relatively shallow (<2.5 km) crustal section of low-density/high-porosity rocks.

In their commentary, B&P remind us of the high-quality heat-flow data obtained by Lewis *et al.* (1988) in British Columbia. These data also show a steep north-trending gradient west of the Quaternary volcanic arc, and B&P cite them in support of a deeper heat source. However, superposition of the Oregon and British Columbia gradients reveals that they are similarly steep, and therefore share a similarly shallow source depth.

DISCUSSION

We have always been careful not to completely discount the model for the deeper thermal structure favored by Blackwell and colleagues. Further, we do not regard our own version of the heat-flow map (Fig. 1) as a proxy for the deep thermal structure, but rather as a prediction of the thermal conditions that might be expected at the depths of conventional measurements. In fact, our own numerical-modeling experiments showed that the thermal observations, taken alone, can be explained in terms of either (1) a laterally extensive midcrustal heat source or (2) a narrower, spottier deep heat source that is confined to the Quaternary arc and is flanked by relatively shallow heat-flow anomalies caused by regional groundwater flow (Ingebritsen *et al.*, 1992). Certain of the thermal observations do require significant lateral heat transfer *via* groundwater flow, including some flow in the older (>7 Ma) volcanic rocks (e.g. Fig. 4, SUNEDCO 58-28 and EWEB-CL). The deeper thermal structure will not be uniquely determined without additional deep drilling in areas of high heat flow in the older rocks.

Our study of heat flow in the north-central Oregon Cascades was part of an effort by the U.S. Geological Survey to reassess the geothermal resources of the U.S. part of the Cascade Range. The interdisciplinary USGS effort in north-central Oregon included detailed geologic mapping, analyses of water chemistry from about 800 sites, and geophysical surveys, in addition to analyses of temperature profiles from about 250 sites.

One conclusion was that high heat-flow values west of the Quaternary arc can in fact be explained in terms of lateral outflow of water heated by discrete igneous centers along a relatively narrow zone of magmatism. This "lateral-flow" model has contributed to reduced estimates of the undiscovered geothermal resource (e.g. Muffler and Guffanti, 1995), but defines a clearer geothermal exploration target than models assuming a broad midcrustal heat source.

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